

A TEST OF BLACK HOLE NATAL KICK MECHANISM BY THE FIRST GRAVITATIONAL RADIATION DETECTIONS

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ABSTRACT

We propose a single science case of what can be potentially learned from just a first few LIGO/VIRGO detections.

Subject headings: binaries: close — stars: evolution, neutron — gravitation

1. INTRODUCTION

Next few years will provide first observations of local Universe in gravitational radiation (GR; Abadie et al. 2010). Predicted a century ago (Einstein 1918), GR has never been directly detected (Abadie et al. 2012). One class of likely sources is represented by several known Galactic double neutron star binaries (NS-NS; Kim, Kalogera & Lorimer 2010). Recent theoretical predictions indicate that the most likely sources are, so far undetected, double black hole binaries (BH-BH; Belczynski et al. 2010a). However, the specific relative frequency of these two types of sources is unknown. Here we show that the first detections will not only settle this issue, but will also differentiate between the two leading models of supernova explosion asymmetry and associated BH natal kicks. We found that within the set of physically realistic stellar evolutionary models BH-BH sources vastly dominate over NS-NS binaries. Only one key physical process allows for significant relative contribution of NS-NS sources in the GR signal. The current models behind natal kicks involve asymmetric mass ejection in supernova explosions leading to high NS kicks and small BH kicks. However, if the first few tens of GR detections contain even a single NS-NS binary, it will indicate that BHs receive high natal kicks and some other kick mechanism (e.g., asymmetric neutrino emission) operates at the BH formation. Our study demonstrates how GR observations may be used to gain qualitatively new insights into physical processes that are hard to reach via electromagnetic observations. We anticipate our case to be a starting point to GR related science with NS/BH binaries. Further examples, that will require more detections, may include assessment of the existence of the mass gap between NSs and BHs (Belczynski et al. 2012), and tests of common envelope evolution that is the key factor in the formation of NS-NS and BH-BH binaries (Dominik et al. 2012).

2. CALCULATIONS

Most massive stars are found in binary systems (Goodwin et al. 2007). While stars evolve each binary is a subject to either component merger during common envelope (CE) phases (Webbink 1984) or disruption during supernova (SN) explosions (Tauris & Takens 1998) in which components form NSs or BHs. The surviving binaries form double compact objects: NS-NS, BH-BH or mixed

BH-NS systems. These remnant systems are subject to angular momentum loss via emission of GR and their orbital separation decreases (Peters & Mathews 1963; Weisberg & Taylor 2005). Finally, two compact objects collide and merge into a single compact object giving a rise to a strong GR signal. The LIGO/VIRGO network of ground-based interferometric observatories was designed to search for these signals (<http://www.ligo.caltech.edu/>; <https://www.cascina.virgo.infn.it/>). Initial observations were finished in 2012 but no GR signal was found. The instruments are being upgraded and the advanced network will resume its operation in 2015 with increased sensitivity.

We have employed a set of publicly available evolutionary models (www.syntheticuniverse.org) that provide physical properties and Galactic merger rates (\mathcal{R}_{MW}) of NS-NS and BH-BH binaries. These merger rates include crucial physics revisions (winds, SN, CE) and are used here for the first time to assess the detectability of sources in GR. The calculations of the merger rates were obtained with the **StarTrack** population synthesis code (Belczynski et al. 2008). We have chosen 10 physically realistic models, each testing one unknown in some evolutionary process leading to the formation of NS-NS/BH-BH binary. In each model 2×10^6 primordial binaries were evolved. For each model it was tested whether the CE phase is likely to prevent the formation of NS-NS/BH-BH binary or not (Belczynski et al. 2007). We have converted the merger rates to the advanced LIGO/VIRGO detection rates ($\mathcal{R}_{\text{LIGO}}$) assuming the constant density of Milky Way-like galaxies at the level $\rho_{\text{gal}} = 0.01 \text{ Mpc}^{-3}$ in local Universe. We have adopted $d_0 = 450 \text{ Mpc}$ as the advanced LIGO/VIRGO horizon for NS-NS binary (optimally oriented source with signal-to-noise ratio of 8) with chirp mass $\mathcal{M}_{\text{c,nsns}} \equiv (M_1 M_2)^{3/5} (M_1 + M_2)^{-1/5} = 1.2 \text{ M}_{\odot}$ where individual NS masses are $M_1 = M_2 = 1.4 \text{ M}_{\odot}$. The horizon for a double compact object with a given chirp mass $\mathcal{M}_{\text{c,dco}}$ is calculated with $d = d_0 (\mathcal{M}_{\text{c,dco}} / \mathcal{M}_{\text{c,nsns}})^{5/6}$. Finally, the detection rate is obtained with:

$$\mathcal{R}_{\text{LIGO}} = \rho_{\text{gal}} \frac{4\pi}{3} \left(\frac{d_0}{f_{\text{pos}}} \right)^3 \left\langle \left(\frac{\mathcal{M}_{\text{c,dco}}}{\mathcal{M}_{\text{c,nsns}}} \right)^{15/6} \right\rangle \mathcal{R}_{\text{MW}} \quad (1)$$

where factor $f_{\text{pos}} = 2.26$ takes into account the non-uniform pattern of detector sensitivity and random sky orientation of sources. We first calculate the cube of $(\mathcal{M}_{\text{c,dco}} / \mathcal{M}_{\text{c,nsns}})^{5/6}$ and then take an average over all

double compact objects within a given group (e.g., BH-BH). Galactic rates and chirp masses that enter to eq. 1 are the combination (50%–50%) of results of evolutionary calculations for two stellar populations: one with typical solar chemical composition ($Z = 0.02$) and one with low metallicity ($Z = 0.002$). The investigation of $\sim 30,000$ Sloan Digital Sky Survey galaxies revealed that recent (~ 1 Gyr) star formation was bimodal with about half stars formed with high and half with low metallicity (Panter et al. 2008).

The projected advanced LIGO/VIRGO detection rates are listed in Table 1. The standard model (S) employs current best bets on various physical parameters that are not yet fully constrained but play an important role in the formation of double compact objects. During CE physical values of donor binding energy are used (Xu & Li 2010), maximum NS mass is adopted at $M_{\text{NS,max}} = 2.5 M_{\odot}$ (Lattimer & Prakash 2010), NS natal kicks are taken from observations (Hobbs et al. 2005) as single Maxwellian with $\sigma = 265 \text{ km s}^{-1}$, BH kicks are smaller and obtained within the framework of mass ejection mechanism (Fryer et al. 2012), compact object mass spectrum is based on rapid supernova explosions (Belczynski et al. 2012), stellar winds are revised for the effects of clumping (Belczynski et al. 2010b) and mass transfer episodes are non-conservative with 50% mass retained in a binary (Meurs & van den Heuvel 1989). In models V5 and V6 we adopt $M_{\text{NS,max}} = 3.0, 2.0 M_{\odot}$, respectively. Natal kicks are decreased for NS to $\sigma = 132.5 \text{ km s}^{-1}$ in V7. High BH kicks ($\sigma = 265 \text{ km s}^{-1}$) and no BH kicks are adopted in V8 and V9, respectively. Delayed supernovae are employed in V10. Wind mass loss rate is decreased by factor 2 in V11. Conservative and fully non-conservative mass transfer is assumed in V12 and V13, respectively.

3. RESULTS

It is found that BH-BH mergers vastly dominate GR source population independent of evolutionary uncertainties. For example, in our standard evolutionary scenario BH-BH is $\gtrsim 400$ times more likely to be the first ever detected GR source than NS-NS merger. Only in one model

with high BH kicks (V8) NS-NS are a noticeable contribution ($\lesssim 1/10$) in overall binary source population. These high kicks tend to disrupt already rare massive progenitor binaries and significantly decrease the BH-BH formation rates. This model disfavors kick mechanism that is based on asymmetric mass ejection during supernova explosion that was adopted in all other models. At the NS formation, exploding stars tend to be massive ($10 - 20 M_{\odot}$) in relation to the NS mass ($1.4 M_{\odot}$) and even a small asymmetry in large ejected mass imparts a significant angular momentum kick on a proto-NS. At the BH formation the picture is qualitatively different, as the mass of a dying star is similar to the mass of a BH that is being formed. Most of the star mass is removed prior the BH formation via intense stellar winds (e.g., Luminous blue variable phase, Wolf-Rayet phase) not expected to operate for NS progenitors. Therefore, at the BH formation mass ejection is small or none and does not translate into a significant natal kick.

If any NS-NS mergers are found in the first few tens of GR detections, the most likely process to eliminate the BH-BH binaries are high natal kicks. In such a case some other than mass ejection kick mechanism must operate at least for BHs. Neutrino emission, and associated asymmetries (e.g., Lai 2001 and references therein), that is rather insensitive to the compact object mass or ejected mass would be then a potential alternative for the kick mechanism. If in fact most massive binaries are violently disrupted at the BH formation inter-galactic space should contain free floating single BHs potentially detectable via microlensing observations (<http://ogle.astrouw.edu.pl/>). At this moment, arguments based on electromagnetic observations for high BH kicks (Kuulkers et al. 2012) and no BH kicks (Mirabel & Rodrigues 2003) are being put forward. Here, we have demonstrated that near-future GR observations may provide useful insights into the unknown BH natal kick mechanism.

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TABLE 1
ADVANCED LIGO/VIRGO DETECTION RATES [yr^{-1}] ^a

Model	NS-NS	BH-NS	BH-BH
S	3.9 (1.3)	9.7 (5.1)	7993.4 (518.7)
V5	3.9 (1.3)	9.4 (4.8)	8057.8 (533.7)
V6	3.9 (1.3)	9.3 (4.7)	8041.7 (523.6)
V7	5.0 (1.5)	14.8 (8.3)	8130.1 (574.2)
V8	3.9 (1.3)	1.2 (0.3)	172.2 (14.0)
V9	3.9 (1.3)	11.8 (6.7)	8363.6 (654.9)
V10	5.2 (1.7)	5.7 (4.9)	7762.7 (487.0)
V11	3.9 (1.1)	10.5 (6.3)	12434.4 (888.1)
V12	11.7 (0.8)	7.6 (5.8)	8754.6 (275.3)
V13	3.7 (0.9)	76.9 (62.1)	1709.6 (966.1)

^a Optimistic (realistic) rates are given under assumption that CE phase initiated by Hertzsprung gap donors with no clear core-envelope structure may lead to the formation of double compact object binary (always halts binary evolution).